



Original communication

Estimation of stature using lower limb measurements in Sudanese Arabs

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ABSTRACT

Objectives: The estimation of stature from body parts is one of the most vital parts of personal identification in medico-legal autopsies, especially when mutilated and amputated limbs or body parts are found. The aim of this study was to assess the reliability and accuracy of using lower limb measurements for stature estimations.

Material and methods: The stature, tibial length, bimalleolar breadth, foot length and foot breadth of 160 right-handed Sudanese Arab subjects, 80 men and 80 women (25–30 years old), were measured. The reliability of measurement acquisition was tested prior to the primary data collection. The data were analysed using basic univariate analysis and linear and multiple regression analyses.

Results: The results showed acceptable standards of measurement errors and reliability. Sex differences were significant for all of the measurements. There was a positive correlation coefficient between lower-limb dimensions and stature (P -value < 0.01). The best predictors were tibial length and foot length. The stature prediction accuracy ranged from ± 2.75 –5.40 cm, which is comparable to the established skeletal standards for the lower limbs.

Conclusion: This study provides new forensic standards for stature estimation using the lower limb measurements of Sudanese Arabs.

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1. Introduction

The primary challenge for any medico-legal investigator in identifying unknown human remains is the development of a biological profile via the estimation of race, sex, age and stature.¹ This biological profile can dramatically narrow down the pool of possible victim matches. These profiles are particularly useful in countries such as Sudan, where facilities with the capacity to identify traditional markers (e.g., DNA or dental) that can be used for final identification confirmation are not readily available. The remains, which are frequently the result of wars, airplane crashes, traffic accidents, criminal mutilation and dismemberment and other mass disasters, are present in different forms, for example, skeletal or dismembered and mutilated body parts. Therefore, stature estimation standards requiring complete skeletons or

complete long bones may not be applicable. Under such conditions, devised standards using different parts of the skeleton or limbs may be a practical alternative. It is also generally accepted that the most accurate biological profile is established using contemporary population-specific standards.²

The established linear relationship between stature and various body parts and the long bones of an individual has formed the basis of stature estimation trials conducted using different body parts e.g., Krishan et al.³ Stature has been estimated from the skull and cephalo-facial anthropometry,^{4–6} the sternum and hip bones,^{7,8} the vertebrae,^{9,10} the long bones and their fragments,^{11–16} the small bones of the hand and foot^{17,18} and hand measurements.^{1,2} The foot and its bones, footprints and the tibia have been shown to be relatively accurate biological tools from which identification can be made.^{19–21} This finding has been confirmed by published literature on the estimation of sex from foot bones and foot dimensions^{22,23} and tibial dimensions,²⁴ as well as unique features of the foot and footprints.²⁵ Previous studies of various populations using measurements of lower limb parts, such as foot bones,^{15,18} foot dimensions,^{26–29} foot prints³⁰ and tibial dimensions,^{31–34} demonstrated the forensic utility of these measurements for estimating stature. An extensive literature review

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revealed that previous researchers have studied percutaneous measurements of different bones of lower limbs or of feet alone, but only a few studies have correlated leg and foot measurements for the estimation of stature. Ozaslan et al.³² carried out a study of the correlation between stature and lower limb measurements among Turks. The authors reported a positive correlation between tibial and foot length and stature. They also observed that the best predictor of stature is the tibial length. Sogar and Sharma³⁵ estimated stature from tibial and foot length and foot breadth among Indians. They also observed that the tibial length gives better predictions of stature than foot length or breadth.

Racial and ethnic variations arise among populations from different regions. Hence, each ethnic group requires a different forensic standards, for which a region-based study of subjects is necessary.³⁶ There are currently no population-specific standards for estimating stature among the Sudanese Arab population. Thus, the purposes of the present study were to analyse the relationship between the measurements of the lower limbs and stature and to devise linear and multiple regression equations to estimate the stature of Sudanese Arabs using these measurements.

2. Materials and methods

2.1. Sample

A group of 160 normal, healthy, Sudanese Arab volunteers, consisting of 80 males and 80 females, was recruited from among the companions of patients undergoing surgery in an obstetrics and gynaecology referral clinic at Khartoum Teaching Hospital over a period of 4 weeks. Volunteers were recruited between the hours of 8:00 am and 10:00 am to avoid the influence of diurnal variation. The subjects were aged between 25 and 30 years. The mean age of the individuals was 27.5 ± 1.67 years for males and 27.2 ± 1.6 years for females. The study has received ethical approval from the Ethical committee of the Faculty of Medicine, University of Khartoum (2010-MAR-1). The subjects were required to sign a consent form and then were asked to complete a questionnaire that gathered basic demographic data and asked general questions (e.g., tribe and economic status). All of the subjects were right-handed. None of the subjects had a history of chronic illness, trauma or physical deformity that might affect stature or lower limb dimensions.

2.2. Measurements

The stature and four lower limb dimensions of each subject were measured using standard anthropometric instruments in units of centimetres rounded to the nearest millimetre. All of the lower limb measurements were obtained from the subject's left side, according to the procedure described by the International Biological Program.^{32,37} Necessary precautions were taken while measuring the subjects. The instruments were checked regularly for accurate readings. All of the measurements were obtained in a

well-lit room and repeated three times, and the means of the measurements were recorded. These measurements included the parameters detailed below.

2.2.1. Stature

Stature was measured in centimetres using a Harpenden portable stadiometer (Holtain Ltd., Crosswell, UK). The subjects were asked to stand barefoot on the platform of the stadiometer with the feet in close contact with each other, the trunk braced along the vertical board and the eyes looking forward. The face was adjusted on the Frankfurt plane, and then the projecting horizontal sliding bar was brought to the vertex.³⁴

2.2.2. Tibial length

Tibial length was measured on the subjects while seated with the knees in a semi-flexed position. The measurements were taken from the most prominently palpable portion of the medial condyle of the tibia to the tip of medial malleolus using a Harpenden anthropometer.³¹

2.2.3. Bimalleolar breadth

Bimalleolar breadth was measured as the distance between the most medial projection of the medial malleolus and the most lateral projection of the lateral malleolus using a digital sliding calliper (Mitutoya, Aurora, IL, USA).³⁷

2.2.4. Foot length

Foot length was measured using a Harpenden anthropometer as the straight distance between the most posterior and prominent part of the heel (the pterion) to the most distal part of the longest toe of the foot (the acropodion) as the subject stood upright with equal pressure on both feet.³⁸

2.2.5. Foot breadth

Foot breadth was measured using a Harpenden anthropometer as the straight distance between the metatarsal fibulare and the metatarsal tibiale, with the foot in a fully 'loaded' position.²⁹

2.3. Statistical analysis

The statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS), version 14. A precision study was conducted before the primary data collection. The stature and lower limb dimensions of the same 10 subjects were measured on three different evaluation days, with 2 days between the re-measurements. Intra-observer error was calculated to be within the acceptable ranges for all of the measurements ($r > 0.9$; r TEM $< 5\%$).³⁹ The means, standard deviations, ranges (minimum and maximum) and differences were used to summarise the anthropometric measurements. An independent t -test was used to test for differences between the mean measurements. Pearson's correlation coefficients (r) were calculated to measure the strength of the correlation between stature and the lower limb

Table 1
Descriptive statistics for stature and lower limb measurements (in cm) in both sexes.

Parameter	Males				Females				Independent t -test	
	Mean	SD	Min	Max	Mean	SD	Min	Max	T	P (2-tailed)
Stature	174.71	5.72	161.40	187.60	160.43	5.49	146.20	172.40	16.654	0.000***
Tibial length	41.53	2.09	36.20	46.50	38.31	2.05	33.10	42.70	10.139	0.000***
Bimalleolar breadth	6.81	0.47	5.90	7.70	5.72	0.34	5.00	6.50	17.398	0.000***
Foot length	26.43	1.27	23.90	30.00	24.06	1.04	21.80	26.40	13.254	0.000***
Foot breadth	9.69	0.74	8.00	11.20	8.34	0.47	7.30	9.20	14.319	0.000***

SD: Standard Deviation.

*** The t -test was significant at the 0.001 level (2-tailed).

Table 2
Correlation between stature and lower limb measurements in both sexes.

Variable	Value of <i>r</i>	
	Male	Female
Tibial length	0.829***	0.820***
Bimalleolar breadth	0.349**	0.367***
Foot length	0.773***	0.622***
Foot breadth	0.449***	0.317**

** Significant at the 0.01 level (2-tailed).

*** Significant at the 0.001 level (2-tailed).

measurements. Linear and multiple regression equations for stature estimation were developed using the lower limb dimensions. The predictive value of all of the equations was compared by substituting the minimum, maximum and mean values of the measurements in their respective regression equations and then calculating the estimated stature.¹⁹

3. Results

Descriptive statistics for stature, tibial length, bimalleolar breadth, foot length and foot breadth for both sexes are presented in Table 1. When comparing the equality of the means of the males and females, all of the measurements were significantly larger for males than for females (P -value < 0.001). Therefore, sex-specific correlation coefficients were calculated, and regression analyses were performed.

Table 2 illustrates the correlation coefficients of the left lower limb dimensions with stature in both sexes. All of the measurements showed statistically significant correlation coefficients with stature (P -value < 0.01). The correlation coefficients of the length measurements were greater than those of the breadth measurements for both sexes. Additionally, the greatest correlation was observed for tibial length for both sexes ($r = 0.829$ for males and $r = 0.820$ for females). The lowest correlation coefficients were observed for bimalleolar breadth for males ($r = 0.349$) and for foot breadth for females ($r = 0.317$).

Linear regression equations and the standard error of estimate (SEE), which predicts the deviation of the estimated stature from the actual stature (lower values indicate more reliable stature estimates), were derived for the stature estimations for both the males and the females for each individual lower limb measurement, as shown in Table 3. The SEE was between ± 3.22 (tibial length) and ± 5.4 (bimalleolar breadth) for the male sample and was between ± 3.15 (tibial length) and ± 5.23 (foot breadth) for the female sample. The regression coefficients were found to be statistically significant for all of the derived equations. The predictive value and the coefficient of determination were maximised for the estimation of stature from tibial length for both sexes.

Sex-specific multiple regression equations were formulated to assess whether stature prediction accuracy was improved by using multiple variables (Table 4). The stepwise regression revealed a lower SEE for both sexes (± 2.75 for males and ± 2.88 for females), and the models of estimate that were developed used the same variables for each sex. The variables that were weighted most

Table 4
Multiple regression equations for the estimation of stature (in cm) from lower limb measurements.

Sex	Regression equation	SEE	R^2	P -value
Male	$S = 63.37 + 1.55 \times TL + 1.78 \times FL$	2.75	0.769	<0.001
	$S = 72.89 + 2.16 \times TL + 1.75 \times BMB$	3.14	0.707	<0.001
	$S = 82.57 + 3.70 \times FL - 0.58 \times FB$	3.66	0.600	<0.001
Female	$S = 55.57 + 1.82 \times TL + 1.47 \times FL$	2.88	0.731	<0.001
	$S = 68.37 + 2.09 \times TL + 2.12 \times BMB$	3.10	0.688	<0.001
	$S = 82.44 + 3.34 \times FL - 0.28 \times FB$	4.34	0.388	<0.001

S = stature, TL = tibial length, BMB = bimalleolar breadth, FL = foot length, FB = foot breadth, R^2 = Coefficient of Determination, SEE = Standard Error of Estimate.

strongly in the stepwise regression models for both sexes were tibial length and foot length. In addition, two formulae were developed for use when the lower limb parts are found to be dismembered; one formula involves the leg alone, while the other formula is for the foot alone. The SEE from the model using the tibial length and bimalleolar length showed lower values for both sexes (± 3.14 for males and ± 3.1 for females) than the model using foot length and foot breadth (± 3.66 for males and ± 4.34 for females).

Table 5 presents a comparison of the actual and estimated statures from different lower limb measurements using linear and multiple regression equations. Greater variations were observed in the minimum and maximum values. In both sexes, the mean value estimates were close to the actual statures because the regression equations are calculated from measures of central tendency.

4. Discussion

Lower limb dimensions have considerable value in the forensic sciences, especially for stature estimation, because previous studies have established that the lower limb bones have a greater predictive validity regarding stature than the bones of the upper limbs.³¹ The general shape and size of the foot are unique to each person,²⁶ and the foot's anatomical structure shows ethnic and regional variations resulting from congenital conditions, climatic factors, physical activities, nutrition conditions and type of shoe worn.²⁰

This study was conducted using 160 subjects who were between 25 and 30 years old. This age was chosen to ensure maturity and to avoid issues of stature reduction, as previous studies have shown that although stature at 18 years of age is generally accepted as being that of an adult, the median age for attaining full stature in males is 21.2 years, with growth continuing in 10% of males until 23.5 years.⁴⁰ Stature starts to decline after the age of 30 years among black individuals⁴¹ and after the age of 40 years among white individuals,⁴² although Galloway⁴³ contradicted this finding and devised a new formula that proposed 45 years as the age of onset for age-related decreases in stature.

The results of this study showed that stature and the studied lower limb dimensions are significantly greater among males than among females (P -value < 0.001). This finding agrees with the results of other studies.^{29,32,44} This fact has been attributed to earlier skeletal maturity among girls compared to boys, which gives boys

Table 3
Linear regression equations for the estimation of stature (in cm) from lower limb measurements.

Males				Females			
Regression equation	SEE	R^2	P -value	Regression equation	SEE	R^2	P -value
$S = 80.59 + 2.27 \times TL$	3.22	0.687	<0.001	$S = 76.44 + 2.19 \times TL$	3.15	0.673	<0.001
$S = 145.56 + 4.28 \times BMB$	5.40	0.122	<0.01	$S = 126.27 + 5.97 \times BMB$	5.13	0.135	<0.001
$S = 82.67 + 3.48 \times FL$	3.66	0.597	<0.001	$S = 81.73 + 3.27 \times FL$	4.32	0.387	<0.001
$S = 141.14 + 3.46 \times FB$	5.15	0.202	<0.001	$S = 129.52 + 3.77 \times FB$	5.23	0.101	<0.01

S = stature, TL = tibial length, BMB = bimalleolar breadth, FL = foot length, FB = foot breadth, R^2 = Coefficient of Determination, SEE = Standard Error of Estimate.

Table 5

Comparison of actual stature and estimated stature (in cm) from lower limb measurements.

Parameters	Males			Females		
	Estimated stature			Estimated stature		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
TL	162.76	186.15	174.86	148.93	169.95	160.34
BMB	170.81	178.52	174.71	156.12	165.08	160.42
FL	165.84	187.07	174.65	153.02	168.06	160.41
FB	168.82	179.89	174.67	157.04	164.20	160.96
TL + FL	162.02	188.84	174.79	147.86	172.09	160.66
TL + BMB	161.41	186.10	174.50	148.15	171.39	160.56
FL + FB	166.36	187.07	174.74	153.46	168.04	160.46
Actual stature	161.40	187.60	174.71	146.20	172.40	160.43

TL = tibial length, BMB = bimalleolar breadth, FL = foot length, FB = foot breadth.

an extra two years of growth.²⁹ Additionally, nutritional, geographic and climatic influences on stature have been reported.³⁸ When the means and ratios of tibial length, bimalleolar length, foot length and foot breadth to stature (expressed in percentages) were compared with the findings of similar, previously published studies, differences were found among populations (Table 6).^{27,28,31–34,36,38,45–48} The results of this study showed that the mean tibial length and tibia to stature ratio of Sudanese Arabs are higher than those of Egyptian, Indian and Turkish males and females but are lower than those of Nigerians. These differences are perhaps due to genetic and environmental factors that result in a higher tibia to stature ratio for sub-Saharan Africans.¹² The bimalleolar breadth and its ratio to stature were found to be lower among Sudanese Arabs than among Egyptians, which may indicate differences in frame sizes attributable to genetic factors, nutritional factors and physical activity levels. However, the feet of Sudanese Arab males were found to be larger than those of Indian, Turkish and Mauritian males, while the feet of Sudanese Arab females were found to be longer and slimmer than those of Turkish and Indian females. The foot length to stature ratio and foot breadth to stature ratio show values similar to those reported in other studies. It is known that the general shape and size of the foot remain permanent throughout life after reaching adult length by the age of 16 years for males and 14 years for females. However, the spread of the toes, which mainly affects foot breadth, may be affected by shoe-wearing habits or changes in physical activity.^{3,19,26,49} Therefore, these differences between Sudanese Arabs and other populations can be attributed to factors related to climate, nutrition, physical activity, shoe-wearing habits and congenital conditions.^{20,49,50}

In the evaluation of the correlation between stature and the four dimensions used in this study, the measurements were found to be significantly correlated with stature. The correlation coefficient

between stature and the leg dimensions was greater for tibial length ($r = 0.829$ for males, 0.820 for females) compared to breadth, that is, bimalleolar breadth ($r = 0.349$ for males, 0.367 for females), for both sexes. This finding agrees with various studies that reported that tibial length is a good predictor of stature.^{31–33} The results obtained in this study showed a significant correlation between stature and bimalleolar breadth for both sexes. This finding disagrees with results obtained from Egyptians, among whom there is a reportedly significant sexual dimorphism for this measurement, but no correlation between stature and bimalleolar breadth was found for either sex.³³ This finding might indicate that although the general body frames of Sudanese Arab males and females are different, as indicated by their sexual dimorphism, they still have similar genetics and body proportions.

In the present study, foot length and breadth were found to be statistically significantly correlated with stature. Among other studies performed on adult populations using anthropometrical measurements, Jasuja et al.⁴⁵ examined the relationship of foot measurements with stature and found that the length of the foot is more strongly correlated with stature than the foot breadth. Krishan and Sharma²⁹ found the same correlation. Kanchan et al.³⁶ and Sanli et al.²⁸ reported that the stature of an individual is significantly correlated with foot length for both sexes. With regard to the positive and linear relationship between stature and foot dimensions reported in this study, the Pearson's correlation coefficient was found to be greater for the length dimension ($r = 0.773$ for males, $r = 0.622$ for females) than for the breadth dimension ($r = 0.449$ for males, $r = 0.317$ for females). These results agree with the previous findings and with the findings of Krishan et al.³ among sub-adult females, as these results show that foot length has a closer relationship with stature than foot breadth. However, these results are not in concordance with the results of Kanchan et al.,³⁸ who reported that the maximum correlation was exhibited by foot breadth in females, and of Ozden et al.,²⁷ who found a weak, insignificant relationship between stature and foot width among females. These variations could be due to biological and environmental factors affecting the studied populations.

In assessing the accuracy of the sample using single bones, the SEE was lowest when using the measurements of tibial length for both sexes (SEE ± 3.15 – 3.22 cm). This result is comparable to those of previous studies using tibia measurements, for example, those of Mohanty³¹ (SEE ± 2.87 – 3.44) and of Ozaslan et al.³² (SEE ± 3.86 – 4.39). However, this result is lower than that obtained by El-Meligy et al.³⁹ (SEE ± 6.51 – 8.24). After the tibia, the next best predictor of stature was foot length (SEE ± 3.66 – 4.32), which was better than foot breadth (SEE ± 5.15 – 5.23). This finding is in concordance with that of Jasuja et al.,⁴⁵ who reported that stature was estimated with minimal mean error when using foot length and that the error was highest when using foot breadth. Additionally, this finding agrees

Table 6

Comparison of the present study with similar previously published findings on the lower limb measurements expressed in percentages to stature.

Study	Place	Stature		TL		BMB		FL		FB	
		M	F	M	F	M	F	M	F	M	F
The present study	Sudan	174.41	160.43	23.81	23.88	3.90	3.57	15.15	15.00	5.56	5.20
Kanchan et al. ³⁶	India	166.39	159.56					15.63	14.9		
Didia and Nduka ⁴⁶	Nigeria	183.44	162.96	25.44	25.25						
Zeybek et al. ²⁰	Turkey	174.19	161.69					14.69	14.27	5.49	5.29
Krishan and Sharma ²⁹	India	168.24	155.72					14.68	14.51	5.65	5.48
Agnihorti et al. ⁴⁸	Mauritius	173.99	159.56					15.00	14.60		
El-Meligy et al. ³³	Egypt	171.43	157.36	22.62	22.21	4.19	3.88				
Ozden et al. ²⁷	Turkey	174.39	160.94					14.93	14.48		
Ozaslan et al. ³²	Turkey	171.97	161.75	22.31	21.72			14.48	13.97	5.41	5.29
Duyar and Penil ⁴⁷	Turkey	174.64		22.32							
Mohanty ³¹	India	161.92	152.00	22.90	23.05						
Jasuja et al. ⁴⁵	India	169.88	160.43					15.10		5.73	

TL = tibial length, BMB = bimalleolar breadth, FL = foot length, FB = foot breadth, M = male, F = female.

with various studies of different populations using foot length. For example, when using the left foot to estimate the stature of Indians, the mean error was 3.53–4.38 for Rajputs,²⁹ while it was 3.84–4.42 for Gujjar males.³⁸ Among Turkish people, as reported by Sanli et al.,²⁸ the mean error was 3.54–4.3 using measurements of the right foot, and according to Ozaslan et al.,³² it was 3.93–44.6 using measurements of the left foot. However, these findings contradict the finding that the mean error was less for foot breadth than for foot length in Gujjar females.³⁸ This low mean error in length for both sexes might suggest that Sudanese Arabs have genetic and body proportion similarities that are greater than anticipated, as improved accuracy is likely to be attributed to a lack of diversity among the study population.

The SEE was decreased when multiple regression models were used for the lower limb dimensions, and this study demonstrated a higher degree of predictive accuracy supported by a lower SEE (± 2.75 – 2.88) and a higher R^2 (0.767 – 0.805) compared to simple linear models. The variables selected in the best models included tibial and foot length for both sexes. This choice might indicate that the accuracy of stature estimation is usually more reliable when the lengths of the lower limbs are used. The accuracy of the sex-specific regression models derived in this study indicated that stature estimation is more accurate for males compared to females when the tibia and foot measurements are used together or when foot dimensions are used alone. However, the prediction is more accurate for females when using the leg measurements (tibial length and bimalleolar breadth). The variation between these two findings might be attributed to environmental factors affecting the foot, such as working patterns or the wearing of shoes.

5. Conclusion

Stature estimations from limbs or dismembered body parts are important for personal identification, especially when the utility of DNA analysis is limited due to economic issues or to other difficulties, such as wars or mass disasters. It is worthwhile to mention that the present study is a pioneering study in forensic anthropology among Sudanese Arabs, despite Sudan's involvement in civil wars for more than two decades. This study successfully reports the relationships between stature and lower limb dimensions. The present study observes that there is sexual dimorphism regarding stature and the other dimensions used. In this study, new Sudanese forensic standards were outlined for stature estimation, and regression equations were derived from the lower limb measurements of Sudanese Arabs. These results indicate that stature can be predicted from such measurements, with an SEE of ± 2.75 – 5.40 cm for both sexes.

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Conflict of interest

There are no conflicts of interest regarding this research or the manuscript.

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